INVESTIGATING PERCEIVED MEANINGS AND SCOPES OF DESIGN FOR ADDITIVE MANUFACTURING

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ABSTRACT

The concept of Design for Additive Manufacturing (DfAM) is gaining popularity along with AM, despite its scopes are not well established. In particular, in the last few years, DfAM methods have been intuitively subdivided into opportunistic and restrictive. This distinction is gaining traction despite a lack of formalization. In this context, the paper investigates experts' understanding of DfAM. In particular, the authors have targeted educators, as the perception of DfAM scopes in the future will likely depend on teachers' view. A bespoke survey has been launched, which has been answer by 100 worldwide-distributed respondents. The gathered data has undergone several analyses, markedly answers to open questions asking for individual definitions of DfAM, and evaluations of the pertinence of meanings and acceptations from the literature. The results show that the main DfAM aspects focused on by first standardization attempts have been targeted, especially products, processes, opportunities and constraints. Beyond opportunistic and restrictive nuances, DfAM different understandings are characterized by different extents of cognitive endeavor, convergence vs. divergence in the design process, theoretical vs. hands on approaches.

Keywords: Design for Additive Manufacturing (DfAM), Early design phases, Design methods, opportunistic DfAM, restrictive DfAM

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1 INTRODUCTION

The enhanced capabilities of new digital manufacturing techniques such as Additive Manufacturing (AM) and 3D Printing are capable of drastically changing the mindset of designers and engineers toward the design process. This change of mindset is beginning to gain traction but remains far from completed and designers' ability to fully exploit the potential of AM is questioned (Thompson et al., 2016). In this context, the need arises for new design methodologies, Design for Additive Manufacturing (DfAM), that can support designers in exploiting the capabilities of these technologies.
DfAM guides designers to consider the opportunities provided by AM such as shape complexity, material complexity, no-need for tooling and customization to mention a few (Kumke et al. 2018). This new way of re-thinking the whole design process raised interest both in academia and industry, leading to the development of methods and frameworks over the past decade (Thompson et al 2016). However, the objectives of these methods are diverse, and some of them target design constraints, rather than new opportunities, mirroring the scope of traditional Design for Manufacturing and Assembly (Boothroyd, 1994).
In consideration of this plurality of objectives, Laverne et al. (2015) reviewed and classified, for the first time, the main DfAM methods into two main categories: opportunistic and restrictive DfAM. As more widely explained in the following section, this differentiation is increasingly diffused in the AM literature, although it has not undergone a validation process yet. This classification might be useful in formalizing DfAM knowledge, which is still an open issue (Kim et al., 2019), as well as in its ongoing standardization (Mani et al., 2017).
The distinction between opportunistic and restrictive methods represents a starting point; however, as it has been currently proposed, this distinction is affected by the following shortcomings:

- Whilst the distinction is intuitively sound, the belonging of specific methods and approaches to one of the two categories has not been universally accepted or subject to rigorous evaluation. It remains an arbitrary decision whether a technique should be considered opportunistic or restrictive.
- The ready acceptance of these two classifications has neglected the exploration of other potentially useful classifications.
- Any definitive classification should be evaluated, recognized as a guiding principle, accepted and internalised by all stakeholders in the field. This would support efficient communication between different actors within the discipline.

Starting from these premises, this paper explores the interpretation of the DfAM concept, which is relatively novel and consequently still fluid. In particular, the paper aims to ascertain the degree of agreement on the distinction between opportunistic and restrictive methods, to understand whether some experts perceive the two classes as antithetic, and to investigate the presence of other latent and yet unelicited classification criteria. The study addresses these issues by gathering feedback from a representative sample of educators active in the teaching of AM and DfAM. Here, the role of educators is considered critical as the future understanding of DfAM will depend on their viewpoint. At the same time, consensus, shared definitions and classifications would benefit educators in achieving international consistency and compatibility of DfAM teaching and learning.
Therefore, this paper aims to investigate this distinction between opportunistic and restrictive methods, look for consensus among experts and explore whether there are other potentially more useful classification criteria.
Section 2 analyses the current uptake of the distinction between opportunistic and restrictive methods. Section 3 describes the approach to determining different interpretations of DfAM, with the results presented in Section 4 and discussed in Section 5. Conclusions are drawn in Section 6 with emphasis on the pursuance of the research objectives and the major implications of this study.

2 BACKGROUND

Laverne et al. (2015) characterised opportunistic DfAM methods as those that lead to the creative exploration of new shapes and concepts. The authors considered methods based on optimization techniques (e.g. parametric and topological), elementary shapes (e.g. lattice structures), bionic structures and features produced by specific AM technologies. Such methods provide designers with an opportunity to extend the possibilities of design thinking, aiming to overcome the fixation on

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constraints imposed by conventional manufacturing techniques (Booth et al., 2017). On the other hand, restrictive DfAM methods address the limitations and constraints of AM technologies such as limited materials and properties, performances and characteristics of AM machines, product manufacturability and quality. Laverne and colleagues also investigated the distribution of the implementation of these methods suggesting that opportunistic and restrictive methods are equally distributed. They also provided case studies where both categories of DfAM were involved. The distinction between opportunistic and restrictive methods became a landmark for successive studies, which embraced and shared this classification. Consistently, the literature shows that AM is characterised by great opportunities and considerable constraints while highlighting the relevance of this process for industrial applications (Thompson et al., 2016).

In general, many scholars agree that opportunistic DfAM is more relevant to the early, more explorative divergent stages of the design process (Kumke et al., 2018; Laverne et al., 2015; Blösch-Paidosh and Shea, 2019; Design Council, 2005) since these methods aim to stimulate creativity and creative ideas (Watschke et al., 2017; Prabhu et al., 2020a; Barclift et al., 2017). On the other hand, restrictive DfAM methods are proven to be more effective as guidelines (Watschke et al., 2017) to be followed in the later, convergent stages of the design process (Kumke et al., 2018; Prabhu et al., 2018a; Reichwein et al., 2020) where the concept is fixed and the design progresses towards manufacture.

Beyond scholars' stances on the role of opportunistic and restrictive DfAM approaches, the two categories have been purposefully used in specific applications concerning design processes and training activities. While the former has focused more on opportunistic methods as a means to improve ideation, the latter has involved predominantly restrictive methods and markedly the use of guidelines to ensure successful printing.

In particular, the integration of specific methods in design and product development processes can be found in the contributions that follow.

- Zhu et al. (2017) focused on restrictive DfAM only, since they were interested in design optimization to ensure geometric consistency of the designed product.
- Laverne et al. (2017) prepared a questionnaire where they asked designers which of the two DfAM methods they usually use. The scope of the questionnaire was to understand the relationship between AM and innovation.
- Blösch-Paidosh & Shea (2019) encouraged the integration of opportunistic DfAM in the early design stages.
- Meisel et al. (2017) took into consideration the whole design process and presented a case study where an existing product had been redesigned with AM techniques. The study showed how using specific DfAM guidelines can significantly reduce manufacturing time and costs, while obtaining new and novel design geometries. In this process, opportunistic methods were mainly used to widen the exploration of the design space, while restrictive ones were leveraged to consider fabrication issues.
- Reichwein et al. (2020) focused on the functionality of the product and used an opportunistic DfAM approach to a larger extent. Their contribution took into account the detailed design phases too.

Other contributions consider DfAM in the training of practitioners and the education of students through workshops and other practical activities, as in the following.

- Prabhu et al. (2020a) underlined the need to further investigate opportunistic and restrictive DfAM as training methods for industry professionals. The scholars used a workshop-based study to introduce opportunistic and restrictive DfAM to industrial practitioners.
- Conversely, Watschke et al. (2017) proposed an academic workshop where opportunistic and restrictive approaches were combined to support the generation of creative solutions concepts in design education.
- Barclift et al. (2017) evaluated students' creativity when performing a design task using opportunistic methods only.
- Prabhu et al.(2018a) investigated the effect of opportunistic and restrictive DfAM methods in education, focusing on engineering students' creative process.

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- Prabhu et al. (2018b) studied the impact of timing in teaching opportunistic and restrictive methods on the students' design processes. The scholars compared two DfAM educational interventions conducted at different points in the academic semester.
- Prabhu et al. (2020b) proved that the order of teaching opportunistic and restrictive DfAM on engineering students can affect the way they approach the design process. This highlights the need for educators to account for the order of presenting content to students.

The above examples show that the distinction between opportunistic and restrictive DfAM is no longer limited to theoretical constructs but is also becoming operationalized. It follows that the classification of DfAM methods is perceived as a necessity by scholars and that more proven categorizations can increase the robustness of future research on the topic. To the best of author's knowledge and based on the analysis of the literature, there are no further classifications of DfAM methods and approaches.

3 METHOD

The introduction revealed the need for increasing formalization of DfAM which would align with ongoing standardization initiatives and inform and support the development of education and training in DfAM.

To investigate educators' current understanding of DfAM and the current diffusion of this topic in tertiary education, the authors implemented an online survey. While a full description of the survey, which is available in an article currently under review, goes beyond the scope of the present paper, a clone is accessible at https://lboro.onlinesurveys.ac.uk/dfam-education-programmes-copy-2 (data will not be saved). Briefly, the survey included questions to pursue the objectives that follow.

- Evaluate the uptake of DfAM in education and specifically to the broader AM field.
- Characterise units of study in which DfAM is taught in terms of the number of students, University level (e.g. Bachelor, Master), training activities (e.g. lectures, hands-on projects), assessment methods, taught DfAM contents, and the relevance of DfAM-related subjects.
- Characterize educators in terms of their experience, University grade, attitude to research DfAM and AM.
- Characterize institutions and programmes that include DfAM education in terms of discipline (e.g. engineering, design), country, etc.
- Elucidating educators' understanding of DfAM, taught DfAM-related topics out of a tentative list extrapolated from Thompson et al. (2016), familiarity with DfAM, and agreement on possible definitions of DfAM, which had been previously collected in the literature.

The survey was completed in spring 2020 by 100 internationally distributed educators that teach AM and claimed to be familiar with DfAM. Out of this sample, 71 educators include DfAM in their taught content. The issues in the last bullet point above were investigated to address the problems identified in this paper. In particular, we considered the answers to the two survey questions below.

1. "What does 'Design for Additive Manufacturing' mean to you?", which represents an open question and, therefore, the respondents were free to answer in an unconstrained way — the analysis of the answers to this question is given in Section 4.1.
2. How pertinent are the definitions or topics below to your understanding of 'Design for Additive Manufacturing'?", which was followed by 17 randomly ordered alternative DfAM meanings extracted from the literature and largely inferable from (Thompson et al., 2016). The respondents answered through a five-point Likert scale ranging from "not at all pertinent" to "extremely pertinent". The analysis of the answers to this question is given in Section 4.2., which includes the 17 options.

The latter followed the former to avoid bias and maximize respondents' freedom of answering the first question.

4 RESULTS

4.1 Open-ended definitions of DfAM

The open-ended questions were analysed using Nvivo (version 12). Keywords indicating individual concepts were identified and coded. To gain additional insight, an affinity diagram was developed to categorize the codes that were cited twice or more. Affinity diagrams are useful for organizing ideas

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into categories based on their underlying semantic similarity and assist the identification of patterns and categories that exist in qualitative datasets (Pyzdek, 2003).
To develop the affinity diagram shown in Table 1, one of the authors worked independently to code the entries and cluster them into categories. At that point, the preliminary categorisation was shared with other two authors, who independently reviewed the pertinence of the coding and clustering. Thereafter, the three authors met and discussed the categories to reach a final consensus., Each author has at least 5 years' research experience in the field of DfAM evidenced by peer reviewed papers.,
The content analysis provided 241 different codes. Codes were subsequently compared to determine which belonged together, thereby forming a Category. Category names are short overarching keywords. The codes were grouped into 7 broader categories (Erlingsson and Brysiewicz, 2017). Table 1 reports the categories with at least five entries (the number of entries in brackets), while the codes with one entry only are grouped for the sake of brevity.

Table 1 Definitions of DfAM (n = 241 themes, n = 100 respondents).

Category	Codes	Frequency
Outcomes (63)	Parts	18
	Products	12
	Performance	10
	Component	4
	Desired function	3
	New functionalities	2
	Lightweight	2
	Other subcategories with an entry	12
Design approaches (48)	Design rules	10
	Design methods	9
	Design tools	4
	Design guidelines	4
	Design thinking	3
	Design process	3
	Other subcategories with an entry	15
Opportunistic DfAM (43)	Capabilities	10
	Advantages	8
	Benefits	6
	Design freedom	5
	Potentials	3
	Use AM freedoms	2
	Investigating design possibilities	2
	Understand and capitalise opportunities	2
	Other subcategories with an entry	5
Restrictive DfAM (42)	Design for Manufacturability	13
	Limitations	10
	Constraints	7
	Restrictions	4
	Factors to consider	2
	Other subcategories with an entry	6
Individual AM processes (7)	*Subcategories with an entry*	7
Optimisation (6)	Optimal use of the manufacturing process	2
	Other subcategories with an entry	4
Uncategorized (32)		32

Four main categories 'Outcomes', 'Design approaches', 'Opportunistic DfAM' and 'Restrictive DfAM' were identified from the codes while the categories 'Individual AM processes' and 'Optimisation' were also identified, but by a limited number of codes. The majority of the elicited definitions included the outcomes of DfAM. These consisted of generic and widely mentioned terms such as 'parts' and 'products' (illustrative definitions given by respondents are reported in italics in the followings).

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'Any tools or methods that are useful for synthesizing and/or refining parts that can be fabricated with AM successfully and/or make use of the freedoms enabled by AM',

More specific product-related outcomes such as 'lightweight', 'quality', 'price', 'complexity', were also frequent.

'Designing a part with lightweight, optimal shape (complex) and manufacturable using AM'.

The 'Design approaches' to achieve these outcomes were also widely reported in the gathered definitions. These included a wide variety of approaches and synonyms such as 'Design rules', 'Design methods' and 'Design tools.'

'Any tools or methods that are useful for synthesizing and/or refining parts that can be fabricated with AM successfully and/or make use of the freedoms enabled by AM.'

The interpretation of DfAM as Restrictive or Opportunistic was also well recognized among our participants, although these classes cannot be considered as fully representative of DfAM-related principles. As evident from Table 1, the distribution of definitions compliant with the two classes is extremely balanced. The most cited Opportunistic DfAM meanings were generic synonyms of opportunities such as 'Capabilities', 'Advantages', 'Benefits', etc.

'Exploiting the potential of AM in the design step and optimize geometries and shape.'

In terms of Restrictive, the most cited terms were 'Design for manufacturability' and 'Limitations', 'Constraints' and 'Restrictions'.

'The process of designing parts or products to take into account the constraints and abilities of an additive manufacturing process.'

Besides the mention of specific AM technologies, which the authors judge misleading to characterize DfAM, and optimization-oriented definitions, there was a long tail of codes that did not clearly match the categories and other codes, or they were mentioned too rarely to justify a new category. These themes included for instance 'Adapted design to end-user', 'Life cycle requirements' or 'New materials'.

'Basically, it can be design methods or tools which consider the functional and mechanical performance and key product life-cycle requirements, including manufacturability, complexity, reliability, time and cost can be optimized leveraging on the unique capabilities of additive manufacturing.'

4.2 Evaluated pertinence of DfAM meanings

The pertinence evaluations attributed by the 100 respondents to the 17 DfAM meanings (see Table 2) were transformed into 17 corresponding ordinal variables. Consistent with the Likert scale used, the values attributed to these variables ranged from 1 to 5. The statistical analyses that follow were performed with the software Stata SE 13.

The variables were firstly used to verify the redundancy of the meanings by submitting them to a Spearman correlation. As a common rule of thumb, values over 0.8 could be considered as an (almost) perfect agreement (Landis and Koch, 1977), which, in the specific case, could be interpreted as a repetition of a definition because of a systematic repetition of pertinence evaluations. The correlation values ranged from -0.03 to 0.75, which led us to conclude that none of the variables' pairs represent fully overlapping DfAM-related concepts.

Therefore, to merge these meanings and capture independent dimensions of DfAM definitions, the same variables were processed with a Principal Component Analysis (PCA). The PCA provides a number of independent dimensions, namely the components, which are featured by their capability of describing the variability of the sample, which is expressed by the eigenvalue and, accordingly, the proportion of explained variability. The extracted components are a linear combination of input variables (here the stated agreement on DfAM meanings) and their calculated weights. In the presented case, each respondent could therefore feature a number of independent variables and their associated values. However, the key point here is to extract and characterize the fundamental independent components and interpret their significance to DfAM.

As a common rule of thumb, those PCs reporting an eigenvalue greater than 1 were processed further to infer the relevant independent dimensions, leading us to focus on five PCs accounting for 67.7% of the data variability. The weights of the original components (first column) on the five selected PCs are reported in Table 2.

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Table 2. Extraction of Principal Components out of the evaluation of pertinence of DfAM definitions (n=100 respondents)

	PCA weights				
Meanings	PC1	PC2	PC3	PC4	PC5
1. Design methods aimed at better exploiting the potentials of Additive Manufacturing	0.11	0.07	0.72	-0.05	-0.11
2. Exploring design methods in which the functional performance and lifecycle considerations of products are optimized to Additive Manufacturing capabilities	0.20	0.25	0.33	-0.34	0.02
3. Design freedoms enabled by Additive Manufacturing	0.26	0.03	0.16	-0.21	-0.04
4. Understanding the constraints in the design of parts to be produced by Additive Manufacturing	0.21	-0.33	0.07	-0.03	0.39
5. Design rules, guidelines and suggestions for parts conform with Additive Manufacturing production technologies in light of their current affordances and constraints	0.19	-0.30	0.21	-0.04	0.31
6. Supporting the choice between traditional and Additive Manufacturing technologies	0.26	-0.33	0.04	0.10	-0.12
7. Supporting the choice between the most suitable AM process for the production of parts or products	0.25	-0.39	-0.12	0.21	-0.16
8. Part consolidation, reducing the number of components	0.31	-0.07	-0.10	-0.16	0.15
9. Designing parts with lattice or cellular structures	0.27	-0.05	-0.12	-0.34	-0.04
10. Utilising Topology Optimization or targeting the creation of lightweight structures	0.30	0.00	-0.30	-0.28	-0.07
11. Design of parts with multiple or composite materials	0.24	0.21	-0.28	-0.13	-0.33
12. Design of products with enhanced functionalities that are enabled by Additive Manufacturing	0.20	0.48	0.02	0.08	-0.08
13. The redesign of a part to make it compatible with Additive Manufacturing production	0.25	0.20	-0.23	-0.08	0.38
14. The development and optimal use of CAD systems for the design of parts that match Additive Manufacturing capabilities	0.24	-0.01	0.04	0.16	-0.45
15. The overcoming of cognitive barriers due to the knowledge of the limitations of traditional technologies	0.27	0.27	0.12	0.33	0.27
16. The change of thinking style previously imposed by past experience and conventional fabrication techniques, which leads to an extension of the design space	0.23	0.22	-0.10	0.57	0.20
17. The research aimed at pushing the boundaries of Additive Manufacturing technologies and its repercussions on design capabilities	0.26	-0.16	0.12	0.27	-0.31

The subsequent interpretation of the PCs based on the weight of the original variables led to the determination of the following DfAM-related concepts (see the attributed names in italics), which are ordered according to diminishing proportion of variability attributed to each PC (in brackets). Where applicable, a tentative definition of DfAM classes featured by high (a.) and low (b.) values of the PCs is given.

1. *General* (38.0%): the weights of the original variables are substantially evenly distributed; as such, all the meanings contribute to a general understanding of the whole scope of DfAM regardless of restrictive or opportunistic nuances.
2. *Explorative* (9.9%): the variables with the highest positive weights feature the overcoming of barriers enabled by AM and divergent design processes. Conversely, variables associated with the most significant negative weights deal with constraints and decision-making processes. This PC has expectedly high values for those respondents with a predominant opportunistic interpretation of DfAM.

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a. Explorative DfAM methods are those intended to guide designers in divergent design activities keeping in mind the opportunities offered by AM.
b. Non-explorative DfAM includes criteria and tools for making decisions on design alternatives with a particular focus on designs' feasibility by means of AM devices.

3. *Conceptual* (7.1%): the variables with highest positive weights feature theoretical constructs concerning the importance of exploiting AM potential, as opposed to markedly negative weights attributed to tasks that involve detailed design phases (topology optimization, choice of materials).
    a. Conceptual DfAM includes techniques that support the consideration of AM potential in the early design phases.
    b. Non-conceptual DfAM tools are those meant to finalize the design of products to be manufactured with AM.
4. *Cognitive* (6.6%): the variables with highest positive weights feature DfAM meanings concerning the change of designers' mindset and the overcoming of their psychological inertia, as opposed to markedly negative weights attributed to practical computer-supported design tasks (topology optimization, lattice structures).
    a. Cognitive DfAM involves the research aimed to change designer's mindset towards the understanding of benefits enabled by the existence and the progress of AM.
    b. Non-cognitive DfAM includes methods and tools that support geometric modifications of designed parts, whose fabrication is enabled by AM capabilities.
5. *Constraint* (6.1%): the variables with highest positive weights feature constraints and guidelines for product design and redesign, mostly oriented to feasibility and compliance with AM technologies. Conversely, variables associated with the most significant negative weights deal with new opportunities offered by AM. This PC has expectedly high values for those respondents with a predominant restrictive interpretation of DfAM.

5 DISCUSSION, LIMITATIONS, AND NEED FOR FUTURE WORK

The analysis of the definitions attributed by the survey's respondents reveals that product and process aspects constitute the foci of DfAM. This finding can be interpreted as the relevance of both procedural/methodological aspects and the outcomes thereof when DfAM is approached. The clear emergence of assigned definitions or clauses ascribable to opportunistic and restrictive DfAM from both the affinity diagram and the outcomes of the PCA shows that the scope of both classes is well internalised by educators in DfAM, irrespective of their awareness and their knowledge of the terminology introduced by Laverne et al. (2015). It follows that, overall, the answers suggest that for our sample of educators, *DfAM is a process which implies design methods, tools and knowledge to achieve a specific outcome by exploiting AM characteristics and mitigating its limitations*. This is in accordance with the published definitions of DfAM (e.g. BS EN ISO/ASTM 52910:2019), showing that there is both a shared agreement of what DfAM means among our sample and between our sample and the published definitions.

The fundamental alignment between what is generally claimed as being part of DfAM and the perceived pertinence of meanings emerges as an outcome of the PCA too. Here, the main PC was a balanced combination of an extensive list of meanings, including opportunistic and restrictive interpretations, as well as other facets. Taken in isolation, this main PC is capable of explaining 40% of data variability. This implies that our sample of respondents is attributed varying values on this PC. This apparently strong result could indicate that the respondents had a different degree of confidence and familiarity towards definitions included in the DfAM literature. However, some other terms distinguishing educators' understanding of DfAM emerged. While opportunistic and restrictive nuances arose, other fundamental interpretations of DfAM are worth highlighting. Other interpretations of the study outcomes include:

- DfAM methods might be attributed to the capability of both expanding the design space enabled by AM and supporting decision-making, especially when it comes to selecting manufacturing technologies.
- DfAM methods might be featured by their varying level of abstraction.
- DfAM ranges from actions to increase engineers' and designers' awareness of the potential benefits of AM to practice-oriented tools targeting redesign and operating on 3D models.

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This study is inherently affected by some limitations. On the one hand, the respondents constitute a large sample of convenience, but the generalizability of the results can be questioned, as the sample is not sufficiently representative of the total engineering educator population. Moreover, the authors have already underlined the reasons for targeting educators in a first instance, but their views could be partially misaligned with the viewpoint of other stakeholders, such as researchers, industrialists, officers of standards bodies, manufacturers of AM machines. While the respondents to our survey possessed a range of confidence in DfAM, their confidence level was not been considered in this first analysis. The authors' future work will nevertheless investigate the views of a broader range of stakeholders. It will be of particular interest to investigate if the distinction between opportunistic and restrictive DfAM is known or intuitively understood also in the AM community at large and markedly outside of the design field. As a further limitation, the processes followed to create categories of definitions and interpret PCs involve subjectivity. Although we have followed best practice and worked in an unbiased way, the analysis performed by different research groups could lead to different outcomes. Acknowledging this, we offer to share our data with researchers willing to repeat the analyses and/or to contribute to the formalization of the DfAM concept and its classifications.

6 CONCLUSIONS

Based on the above discussion of the results, we propose the following final conclusions in response to the research objectives.

- The overall interpretation of DfAM amongst a large international sample of expert educators is in line with the literature and especially with the first attempts to establish standards, in that outcomes, processes, opportunities and constraints are well recognized.
- Neither opportunistic nor restrictive interpretations of AM dominated, despite some respondents expressing a preference for the former or latter. The two classes could be isolated as independent clusters in the PCA, a general knowledge of all DfAM facets appears prevalent among the respondents.
- Other classification criteria, beyond opportunistic and restrictive DfAM methods were found. Although these new classes are not necessarily overlooked within DfAM, our results reveal these additional criteria and show that the opportunistic/restrictive distinction is insufficient to describe the whole breadth of DfAM.

The last bullet point indicates the need for the for standardization the scientific formalization of the field of DfAM without neglecting the breadth of DfAM. In this respect, while many researchers focus on practical aspects and markedly on products, whose design and fabrication is enabled by opportunistic DfAM and constrained by restrictive DfAM, the conceptual and intellectual endeavour behind the development of DfAM (see some well-recognizable PCs) cannot be overlooked. Consequently, more studies are needed to validate the existence of DfAM categories and classification criteria. The expected final outcome will be the formalization of methods and concepts belonging to DfAM classes, articulated according to the opportunistic or restrictive distinction, and, if further evidence is found, the additional criteria that have been elicited in this paper.

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